UNIT THREE

5 ELEMENTARY PARTICLES

Introduction

For many decades physicists have been searching for the ultimate building blocks of particles of which all matter is composed of. These building blocks or particles are elementary particles. After studying the structure of atoms we believed that the electrons, protons and neutrons are the only building blocks of matter (elementary particles). As we look more deeply, although the nature has constructed all material objects out of roughly 100 kinds of atoms, we can understand these atoms in terms of electrons, protons and neutrons. Our attempts to look further within the electron, it seems to be a fundamental particle in the sense that it has no internal structure. i.e. they cannot be explained by as a system of other particles. With the advent of high energy particle accelerators a large number (above 200) of elementary particles have been discovered. If all of these are fundamental particles; it would be impossible to formulate any fundamental dynamic laws of their behaviour. However experiments show that there are only few fundamental building blocks of nature. All others could be explained in terms these fundamental particles. Apart from electron, quarks are fundamental particles. In this chapter we discuss the properties of many of the particles discovered so far and laws that govern their behaviour. Finally we classify these particles. We also discuss about quarks and their properties.

The four basic forces

Physics people are familiar with several forces such as frictional force, tension, viscous force, surface tension, gravitational, electric, magnetic, nuclear radiation, radioactive.... etc. All of these known forces can be grouped into four basic types. In order of increasing strength, these are gravitation, electromagnetism, weak interaction and strong interaction.

1. Gravitational interaction

It is the force between any two masses govern by the equation $F = \frac{GMm}{r^2}$. It is the weakest force in nature and its range is infinity. On the microscopic scale it is very important, but on the microscopic scale it is of no importance at all. However, though the tiny gravitational interaction between one atom of the Earth and one atom our body is negligible, the combined effect, the interactions between all atoms of Earth and all atoms of our body, is observable. The strength of the gravitational force comparing to strong force is 10^{-38}. Every interaction is mediated by a particle. The particle responsible for this interaction is called graviton. It is a massless particle with spin 2. It is due to its weakest strength, it has not been discovered yet.

2. The weak interaction

The forces involved in the process of beta decay and other similar processes producing particles. The weak force between two neighbouring protons is about 10^{-7} times of the strong force between them. This shows that the weak force does not play any role in the binding of nuclei (strong force). The range of this force is very short of the order of 0.001 fm. Nevertheless, the weak force is important in understanding the behaviour of fundamental particles and is critical in understanding the evolution of the universe. The particle responsible for weak interactions are called vector bosons. There are two types of vector bosons. They are (i) $W^{\pm}$ – boson and (ii) Z^{o} – boson. Since the range of the weak interaction is small, vector bosons are massive. The W – vector boson has a spin 1 and charge $\pm$ e and is responsible for ordinary beta decays. Its mass is about 85 times the proton mass (80.4 GeV) But Z^{o}– vector boson is chargeless and has spin 1 and its mass is about 97 times the proton mass (91.2 GeV).

3. The electromagnetic interaction

It is the force due to interaction between fundamental particles. The macroscopic forces such as friction, air resistance, viscous, tension etc. are electromagnetic forces at the atomic level. Within the atom electromagnetic force dominate. The electromagnetic force between neighbouring protons in a nucleus is about 10^{-2} times the strong force between them. Within the nucleus the electromagnetic forces can affect cumulatively hence cannot be neglected with reference to strong force. In determining the stability and structure of nuclei, these two forces have to be considered.

The range of this force is infinity and the particle responsible for this force is photon. Photon is a massless particle with spin1.

4. The strong interaction

This is the force responsible for the binding of nuclear or of that between quarks. In nuclear reactions and decays of fundamental particles this force dominates. Some particles (such as electron) do not feel this force at all. The range of this force is relatively very small of the order of 1fm.

The relative strength of a force determine the time scale over which it acts. Its characteristic time scale is less than 10^{-22} s, whereas in the case of electromagnetic force its characteristic time scale over which it acts ranges from 10^{-14} s to 10^{-20} s. For weak force it is 10^{-8} - 10^{-13} s.

The particle responsible for strong nuclear force is pion, where as gluon is the particle responsible for the strong force between quarks.

Table 5.1: Four basic forces and their properties

Type	Range	Relative strength	Characteristic time (s)	Field particle	Charge	Spin ($\hbar$)	Rest Energy (GeV)
Strong	1 fm	1	$< 10^{-22}$	Pion or Gluon	+e, –e, 0 or 0	1 1	0
Electro Magnetic	∞	10^{-2}	10^{-14}–10^{-20}	Photon	0	1	0
Weak	10^{-3} fm	10^{-7}	10^{-18}–10^{-13}	Vector bosons W^+, W^- and Z^0	+1, –1 and 0	1 1	80.4 91.2
Gravita tional	∞	10^{-38}	years	Graviton	0	2	0

Particles and antiparticles

Protons, neutrons and electrons are particles of which ordinary matter is made. Experiments shown that every particle has an antiparticle. Antiparticles have the same mass and spin as the particles but opposite charge and magnetic moment. For example positron (e^+) is the antiparticle of electron ($\bar{e}$) antiproton ($\bar{p}$) is the antiparticle of proton (p). Four particles the photon, the graviton, neutral pion (π^o), neutral eta meson (η^o) are their own antiparticles. Matter is made up of particles where as antimatter is made up of antiparticles (antiproton, antineutron and positrons)

For example a stable atom of antihydrogen could be constructed from a positron and an antiproton. The properties of this atom would identical to those of ordinary hydrogen atom. Antiparticles of stable particles (such as the positron and the anti proton) are themselves stable. However, when a particle and its antiparticle meet the annihilation reaction can occur. In this reaction particle and antiparticle annihilate to form two or more photons. This reactions occurs in accordance with law of conservation of momentum and energy. Examples :

(i) $\overline{e} + e^+ \rightarrow 2\gamma \ (E_\gamma = 0.511 \text{ MeV})$

(ii) $p + \overline{p} \rightarrow 2\gamma \ (E_\gamma = 938 \text{ MeV})$

Note: An antiparticle is designated by the same symbol as the particle but with a bar over it.

Neutrions are chargeless elementary particles. There are three types of neutrinos. They are electron neutrino (υ_e), muon neutrino (υ_μ) and tau neutrino (υ_τ). Though the electron neutrino and muon neutrino are massless tau neutrino has mass about $320\,m_e$ (where m_e is the mass of the electron). These particles have corresponding antiparticles. They are antielectron neutrino ($\overline{\upsilon}_e$), antimuon neutrino ($\overline{\upsilon}_\mu$) and anti tau neutrino ($\overline{\upsilon}_\tau$).

Since ordinary matter is not composed of neutrino, we cannot distinguish between neutrino and anti neutrino on the basis of matter and antimatter. But the conservation laws in beta decay process can be understood most easily if we define the antineutrino to be the particle that accompanies β^- decay and neutrino accompanies β^+ decay. Another example is consider a lambda (Λ) particle decays to an ordinary neutron. Then antilambda ($\overline{\Lambda}$) decays into antineutron. Similarly negative muon (μ^-) and positive muon (μ^+) are antiparticles of one another because μ^- decays to e^- and μ^+ decays to e^+.

Families of particles

There are more than 200 elementary particles have been discovered. One way to study them is to classify it into different categories based on certain properties and then look for similarities among the classifications. We have already classified according to their types of forces through which their interactactions. In early days of particle physics they were classified according to their masses. It was observed that the lightest particles (electrons, muons and neutrinos) showed one type of behaviour, the heavy mass particles (protons and neutrons) showed a different behaviour and the medium mass particles (pions and kaons) showed a still different behaviour. The Greek word for light is lepton, that for medium is meson and for heavy it is baryon. So elementary particles were three types. Leptons, mesons and baryons. Gradually the original meaning attached to the terms lost their meaning. For example the term lepton was used for light particles, but later heavy leptons were discovered so the name lepton became unsuitable. The classification of particles by mass is now obsolete but we retained the names leptons, mesons and baryons. Now these names describe a group or family of particles with similar properties.

Leptons

Leptons are weakly interacting fermions having spin $\frac{1}{2}\hbar$. These particles take part in weak interactions and electromagnetic interactions when charged. There are six members of this family. They are electron (e^-), electron neutrion (υ_e), muon (μ^-), muon neutrino (υ_μ), tau (τ^-) and tau neutrino (υ_τ). Ofcourse this six family members of leptons have corresponding antiparticles together called antileptons. Positron (e^+), antielectron neutrino ($\bar{\upsilon}_e$), antimuon (μ^+), antimuon neutrino ($\bar{\upsilon}_{\mu^+}$), antitau (τ^+) and antitau neutrino $\bar{\upsilon}_\tau$ are antileptons. The symbol, charge and mass of lepton family are given in the table below.

Table 5.2

Name	Symbol	Charge	Mass in terms of electron m_e
1. Electron	e^-	– 1	1
2. Electron neutrino	υ_e	0	~ 0
3. Muon	μ^-	–1	206.7 m_e
4. Muon neutrino	υ_μ	0	~0
5. Tau	τ^-	– 1	3500 m_e
6. Tau neutrino	υ_τ	0	< 320 m_e

The lepton family

Note: Fermions are particles with half integral spin.

Mesons

Mesons are strongly interacting particles having integral spin. Mesons can be produced in reactions through the strong interactions; they decay to other mesons or leptons through the strong, electromagnetic or weak interactions. For example

$$p + n \rightarrow p + p + \pi^- \text{ or } p + n \rightarrow p + n + \pi^0$$

This is strong interaction. The pions further decay according to $\pi^- \rightarrow \mu^- + \bar{\upsilon}_\mu$ with mean life time 2.6×10^{-8}s, so this is weak interaction.

π^o decays according to $\pi^o \rightarrow \gamma + \gamma$ with mean life time 8.4×10^{-17}s. So this is electromagnetic interaction.

Since mesons are not observed in matter, the classification into particles and anti particles become purely arbitrary. For example π^+ and π^- are antiparticles of one another. Similarly K^+ and K^-. For uncharged mesons such as π^o and η^o, the particle and antiparticles are identical. The antiparticle of neutral kaon (K^o) is ($\bar{K}^o$). K^o and $\bar{K}^o$ are distinct. A list of mesons with their properties is given in table below.

Table 5.3: Some selected mesons

Particle	Anti particle	Charge of particle	Spin $\hbar$	Strangeness of particle	Rest energy (MeV)
π^+	π^-	+1	0	0	140
π^o	π^o	0	0	0	135
K^+	K^-	+1	0	+1	494
K^o	$\bar{k}^o$	0	0	0 + 1	498
η	η	0	0	0	548
ρ^+	ρ^-	+1	1	0	775
η'	η'	0	0	0	958
O^+	O^-	+1	0	0	1869
J/ψ	J/ψ	0	1	0	3097
γ	γ	0	1	0	9460

Note: Strangeness of the particles will be discussed soon.

Baryons

The baryons are strongly interacting particles with half integral spins $\left(\frac{1}{2}, \frac{3}{2}, \frac{5}{2} \cdots\cdots\right)$. Baryons have distinct antiparticles like leptons. Baryons are produced in reactions through strong interactions and decay through electromagnetic and weak interactions. Example.

$$p + p \rightarrow p + \Lambda^{o} + K^{+} \text{ – Strong interaction}$$

$$\Lambda^{o} \rightarrow p + \pi^{-} \text{ – weak interaction}$$

Some selected baryons and their properties are given in table 5.4

Table 5.4: Some selected baryons

Particle	Antiparticle	Charge of particle	Spin $\hbar$	Strangeness of particle	Rest energy (MeV)
p	$\overline{p}$	+1	$\frac{1}{2}$	0	938
n	$\overline{n}$	0	$\frac{1}{2}$	0	940
Λ^{o}	$\overline{\Lambda}^{o}$	0	$\frac{1}{2}$	–1	1116
Σ^{+}	$\overline{\Sigma}^{+}$	+1	$\frac{1}{2}$	–1	1189
Σ^{o}	$\overline{\Sigma}^{o}$	0	$\frac{1}{2}$	–1	1193
Σ^{-}	$\overline{\Sigma}^{-}$	–1	$\frac{1}{2}$	–1	1197
Ξ^{o}	$\overline{\Xi}^{o}$	0	$\frac{1}{2}$	–2	1315
Ξ^{-}	$\overline{\Xi}^{o}$	–1	$\frac{1}{2}$	–2	1322
Δ^{*}	$\overline{\Delta}^{*}$	+2, +1, 0, –1	$\frac{3}{2}$	0	1232
Σ^{*}	$\overline{\Sigma}^{*}$	+1, 0–1	$\frac{3}{2}$	–1	1385
Ξ^{*}	$\overline{\Xi}^{*}$	–1, 0	$\frac{3}{2}$	–2	1533
Ω^{-}	$\overline{\Omega}^{-}$	–1	$\frac{3}{2}$	–3	1672

So far we were discussing the three families of particles. Their structure, interactions, spin and examples are given in Table 5.5 given below.

Table 5.5: Families of particles

Family	Structure	Interactions	Spin	Examples
Leptons	Fundamental	weak, electro magnetic	Half integral	e, υ
Mesons	Composite	weak, electro magnetic, strong	Integral	π, K
Baryons	composite	weak, electro magnetic, strong	Half integral	p, n

Conservation laws

Conservation laws form the back bone of physics. We are familiar with conservation laws like linear momentum, angular momentum, energy etc. These conservation laws are closely connected with the fundamental properties (symmetries) of space and time. We believe, not yet proved contrary, these laws are absolute and inviolable. In the decays and reactions of elementary particle, conservation laws provide a way to understand why some processes occur and others are not observed.

Apart from the well known conservation laws stated above, in nuclear physics there are several others like nucleon number conservation, charge conservation, lepton number conservation, baryon number conservation, strangeness conservation and somany others.

Nucleon number conservation

Consider the alpha decay of a nucleus, such

$$^{235}_{92}U \rightarrow \, ^{231}_{90}Th + \, ^{4}_{2}He$$

The proton number on the L.H.S is 92.

The proton number on the R.H.S. is 90 + 2 = 92

The neutron number on the L.H.S $= 235 - 92 = 143$

The neutron number on the R.H.S. $= (231 - 90) + (4 - 2) = 143$

We balance the proton numbers and also neutron numbers on both sides. This does not mean that in nuclear reactions conserve both proton and neutron number. The next example will clarify this.

Consider the beta decay.

$$n \rightarrow p + \bar{e} + \bar{\upsilon}_e$$

This decay process does not conserve either neutron or proton number. However it conserves the total neutron number plus proton number before and after decay. This is called nucleon number conservation. In all the reaction decays this will be conserved.

Lepton number conservation

The lepton family consists of 6 members. Each member is assigned a number called lepton number (L). The corresponding antiparticles of lepton are assigned a number -1. If the particle is not a lepton, the lepton number is zero. i.e, for all mesons and baryons lepton number is zero. In all reactions and decays, the lepton number before after process must be conserved.

i.e., $L_{e^-} = 1,\ L_{\upsilon_e} = 1,\ L_{\mu^-} = 1,\ L_{\upsilon_\mu} = 1,\ L_{\tau^-} = 1,\ L_{\upsilon_\tau} = 1$

For antiparticles of leptons:

$$L_{e^+} = -1,\ L_{\bar{\upsilon}_e} = -1,\ L_{\bar{\mu}^-} = -1,\ L_{\bar{\upsilon}_\mu^-} = -1,\ L_{\bar{\tau}^-} = -1,\ L_{\bar{\upsilon}_\tau} = -1$$

Examples

(i) $n \rightarrow p + \bar{e} + \bar{\upsilon}_e$

L: $0 \rightarrow 0 + 1 + (-1)$

(ii) $p \rightarrow n + e^+ + \upsilon_e$

L: $0 \rightarrow 0 + -1 + 1$

In both of the decays lepton number is conserved. The lepton number conservation accounts for the emission of antineutrino in β^- decay and the neutrino in β^+ decay.

(iii) $\bar{e} + p \rightarrow n + \bar{\upsilon}_e$

L: $1 + 0 \rightarrow 0 + -1$

$1 \rightarrow -1$

since lepton number is not conserved this reaction is forbidden.

(iv) $p \rightarrow e^+ + \gamma$

L: $0 \rightarrow -1 + 0$

The lepton number is not conserved, this decay is forbidden in nature.

After checking lepton number conservation in general, we have to check whether each type of lepton (e, μ, τ) number is the same on both sides. Then only conservation law is valid.

Examples

1. $$p + \bar{\upsilon}_e \rightarrow e^+ + n$$

$$L_e : 0 + -1 \rightarrow -1 + 0$$

Thus electron type lepton number is conserved

2. $$\upsilon_\mu + n \rightarrow \bar{\mu} + p$$

$$L_\mu : 1 + 0 \rightarrow -1 + 0$$

Here muon type lepton number is not conserved.

3. $$\bar{\upsilon}_\mu + p \rightarrow n + e^+$$

$$L: \quad -1 + 0 \rightarrow 0 + -1$$

Here lepton number is conserved. But this is not observed. This is because muon type lepton number is not conserved.

$$L_\mu : -1 + 0 \rightarrow 0 + 0$$

So muon type lepton number is not conserved.

Thus, lepton number conservation can be put in the following way:

In any process, the lepton numbers for electron type leptons, muon-type leptons and tau-type leptons must each remain constant.

Baryon number conservation

The baryon family also consists of 6 members (p, n, Λ^o, Σ, Ξ^o, Ω^-). Each member is assigned a number + 1 called baryon number (B). The corresponding antiparticles of baryon are assigned $B = -1$. If the particle is not a baryon the baryon number is zero. i.e, all mesons and leptons have B = 0.

$$B_p = 1, \quad B_n = 1, \quad B_{\Lambda^o} = 1, \quad B_\Sigma = 1, \quad B_{\Xi^o} = 1, \quad B_{\Omega^-} = 1$$

For antiparticles

$$B_{\bar{p}} = -1, \quad B_{\bar{n}} = -1, \quad B_{\bar{\Lambda}^o} = -1, \quad B_{\bar{\Sigma}} = -1, \quad B_{\bar{\Xi}^o} = -1, \quad B_{\bar{\Omega}^-} = -1$$

Baryon number conservation states that in any process baryon number must be conserved before and after the process. It may be noted that the nucleon number conservation is a special case of baryon number conservation. Since nucleons are included in baryons we need to go for nucleon conservation separately.

Example

(i) $n \rightarrow p + \bar{e} + \bar{\upsilon}_e$ Beta decay

B: $1 \rightarrow 1 + 0 + 0$ Baryon number conserved

(ii) $p + p \rightarrow p + p + p + \bar{p}$

B: $1 + 1 \rightarrow 1 + 1 + 1 - 1$

$2 \rightarrow 2$

Baryon number is conserved

(iii) $p + p \rightarrow p + p + n$

B: $1 + 1 \rightarrow 1 + 1 + 1$

$2 \rightarrow 3$

Here baryon number is not conserved, so this reaction is forbidden

(iv) $\pi^- \rightarrow \mu^- + \bar{\upsilon}_\mu$

B: $0 \rightarrow 0 + 0$

Baryon number is conserved

Strangeness conservation

First in cosmic rays and later particles were discovered whose behaviour were rather peculiar. These particles were produced in strong interactions in time and short as 10^{-23} s but while decaying they took an enormously long time $\sim 10^{-8}$ s, characteristic of weak interactions. Such particles were called strange particles.

The strange behaviour of the particles was pointed by A Pais. The other strange property of these particles was that they produced in pairs. Why this strange behaviour? The answer to this question came from Gell Mann and Nishijima who assigned a new number to these particles called strangeness number(S). This number was defined analogous to charge specifically for a conservation law based on experimental data.

The strangeness numbers assigned to various particles are given below.

(i) For the kaons (K^+, K°), $S = +1$

For the antiparticles ($\overline{K}^+, \overline{K}^\circ$), $S = -1$

(ii) For the lambda hyperon (Λ°), $S = -1$ and for the corresponding antiparticle ($\overline{\Lambda}^\circ$), $S = +1$

(iii) For the sigma hyperons ($\Sigma^+, \Sigma^-, \Sigma^\circ$), $S = -1$ and for the corresponding antiparticles ($\overline{\Sigma}^+, \overline{\Sigma}^-, \overline{\Sigma}^\circ$), $S = +1$

(iv) For the cascade hyperons (Ξ^0, Ξ^-), $S = -2$ and for the corresponding antiparticles ($\overline{\Xi}^0, \overline{\Xi}^-$), $S = +2$

(v) For the omega hyperon ((Ω^-), $S = -3$ and for the corresponding antiparticle ($\overline{\Omega}^-$), $S = +3$.

Examples

(i) $$K^- + p \rightarrow \Omega^- + K^+ + K^\circ$$

$$S:\ -1 + 0 \rightarrow -3 + 1 + 1$$

$$-1 = -1$$

In this reaction strangeness number is conserved.

(ii) $$\pi^- + p \rightarrow \pi^+ + \Sigma^-$$

$$S:\ 0 + 0 \rightarrow 0 - 1$$

$$0 \rightarrow -1$$

In this process strangeness number is not conserved. So this process is not allowed in nature.

(iii) $$p + p \rightarrow p + p + \Lambda^\circ + K^\circ$$

$$S:\ 0 + 0 \rightarrow 0 + 0 - 1 + 1$$

$$0 \rightarrow 0$$

So strangeness number is conserved. But we cannot say whether this process occurs or not. For this we have to check all other conservation laws. For example suppose we check baryon number conservation, it gives

$$B: 1 + 1 \rightarrow 1 + 1 + 1 + 0$$

$$2 \rightarrow 3$$

So baryon number is not conserved. Thus this process is not allowed.

A very important thing to be noted is that strong interactions and electromagnetic interactions can conserve strangeness number, but weak interaction decays cannot conserve strangeness number. Here strangeness changes by unity so we can write

$\Delta S = 0$ for strong interactions and electromagnetic interactions

$\Delta S = 0, \pm 1$ for weak interactions

Examples

(i) $\Omega^- \rightarrow \Sigma^- + \pi^o$

S: $-3 \rightarrow -1 + 0$

$\therefore$ $\Delta S = -1 - -3 = 2$, so condition that for weak interaction $\Delta S = 0, \pm 1$ is violated

(ii) $\Xi^o \rightarrow n + \pi^o$

S: $-2 \rightarrow 0 + 0$

$\therefore$ $\Delta S = 2$

This being a weak interaction ΔS must be $0, \pm 1$, so strangeness is not conserved. Finally we can define the strangeness number conservation as follows.

In processes governed by strong or electromagnetic interactions the total strangeness number before and after the process must be conserved and in processes governed by the weak interaction strangeness number either remains constant or changes by one unit.

Note: In all processes in addition to above three conservation laws, charge must be conserved as well as spin also must be conserved.

Example 1

Why does a free neutron not decay into an electron and a positron.

Solution

Suppose a free neutron decays into an electron and a positron.

i.e., $n \rightarrow e^- + e^+$

Bariyon quantum number

$$1 = 0 + 0$$

Since baryon quantum number is not conserved the decay is not possible.

Spin is also not conserved.

Example 2

Which of the following reactions can occur state the conservation principles violated by the others.

a) $\Lambda^o \rightarrow \pi^+ + \pi^-$

b) $\pi^- + p \rightarrow n + \pi^o$

c) $\pi^+ + p \rightarrow \pi^+ + p + \pi^- + \pi^o$

d) $\gamma + n \rightarrow \pi^- + p$

Solution

a) $\Lambda^o \rightarrow \pi^+ + \pi^-$

Applying baryon number conservation we get

B : $1 = 0 + 0$ since B is not conserved, this reaction cannot occur

b) $\pi^- + p \rightarrow n + \pi^o$

B : $0 + 1 = 1 + 0$ i.e. baryon number is conserved

Applying charge conservation we get

C : $-1 + +1 = 0 + 0$

i.e. charge is also conserved

Hence this reaction can occur.

c) $\pi^+ + p \rightarrow \pi^+ + p + \pi^- + \pi^o$

Applying charge conservation

C : $1 + 1 = 1 + 1 - 1 + 0$

i.e. charge is not conserved. Hence this reaction cannot occur.

d) $\gamma + n \rightarrow \pi^- + p$

B : $0 + 1 = 0 + 1$ Baryon number is conserved

C : $0 + 0 = -1 + 1$ charge is conserved.

Hence this reaction can occur.

Example 3

A muon (μ^-) collides with a proton, a neutron plus another particle is formed. What is the other particle.

Solution

$\mu^- + p \rightarrow n + x$, where x is the new particle formed.

Applying charge conservation

C : $-1 + 1 = 0 + x$

i.e. $0 = 0 + x$

This implies that x is chargeless.

Applying lepton number, we get

$$\mu^- + p \rightarrow n + x$$

L_μ : $1 + 0 \rightarrow 0 + x$

This implies that x is a μ-lepton. i.e. it is a mu-neutrino.

Example 4

A positive pion collides with a proton, two protons plus another particle are created. What is the other particle.

Solution

$\pi^+ + p \rightarrow p + p + x$, where x is the new particle formed.

Applying charged conservation, we get

C : $1 + 1 = 1 + 1 + x$

This implies that x is chargeless

Applying baryon number conservation, we get

B : $0 + 1 = 1 + 1 + x$

This shows that the baryon number of x is -1. i.e. it is an antiparticle of baryon. In other words x is a chargeless antibaryon.

Example 5

The products of a collision between a fast proton and a neutron are a neutron, a Σ^0 particle and another particle. What is the other particle.

Solution

$p + n \rightarrow n + \Sigma^{o} + x$, where x is the unknown particle formed.

Applying charge conservation, we get

$C: \quad 1 + 0 = 0 + 0 + x$

This implies that x is a charged particle (+ve)

Applying baryon number conservation

$B: \quad 1 + 1 = 1 + 1 + x$

This implies that baryon number of x is 0. i.e. x is not a baryon.

Applying spin conservation, we get

$$S: \quad \frac{1}{2} + \frac{1}{2} = \frac{1}{2} + \frac{1}{2} + x$$

This shows that x is a spinless particle.

Applying strangeness conservation, we get

$S: \quad 0 + 0 = 0 - 1 + x$

This implies that the strangeness of x is 1. Hence x is a positively charged kaon.

Example 6

In proton-proton collision a lambda hyperon, a proton, a positively charged pion and a new a particle are formed. What is the new particle

Solution

$p + p \rightarrow \Lambda^{o} + p + \pi^{+} + x$, where x is the new particle formed

Applying charge conservation, we have

$C: \quad 1 + 1 = 0 + 1 + 1 + x$

This implies that the new particle formed is chargeless.

Since Λ^{o} is a strange particle and the strange particles are formed in pairs. Thus x must be a strange particle.

Applying strangeness quantum number conservation, we have.

$S: \quad 0 + 0 = -1 + 0 + 0 + x$

This implies that x is a particle with strangeness +1.

Hence x is a chargeless kaon (K^{o}).

Example 7

A negative kaon collides with a proton, a positive kaon and another particle are created. What is the other particle.

Solution

$K^- + p \rightarrow K^+ + x$, where x is the unknown particle formed.

Applying charge conservation on both side we get

$C: \quad -1+1=+1+x$

$\quad$ or $x=-1$

This implies that x is negatively charged.

Since kaon is a strange particle, strangeness quantum number must be conserved.

i.e., $S: \quad -1+0=+1+x$

$\quad$ or $\quad x=-2$

This the strangeness of x is –2. Hence the particle must be Ξ^-

Example 8

Name the conservation law that would be violated in each of the following decays.

a) $\pi^+ \rightarrow e^+ + \gamma$

b) $\Lambda^\circ \rightarrow n + \gamma$

c) $\Omega^- \rightarrow \Sigma^- + \pi^\circ$

d) $\Lambda^\circ \rightarrow \pi^- + \pi^\circ$

Solution

a) $\pi^+ \rightarrow e^+ + \gamma$

$L: 0 \rightarrow -1 + 0$	Lepton number not conserved
$B: 0 \rightarrow 0 + 0$	Baryon number conserved
$S: 0 \rightarrow 0 + 0$	Strangeness conserved

b) $\Lambda^\circ \rightarrow n + \gamma$

$L: 0 \rightarrow 0 + 0$	Lepton number conserved
$B: 1 \rightarrow 1 + 0$	Baryon number conserved
$S: -1 \rightarrow 0 + 0$	Strangeness number not conserved

c) $\Omega^- \rightarrow \Sigma^- + \pi^\circ$

$L: 0 \rightarrow 0 + 0$	Lepton number conserved
$B: 1 \rightarrow 1 + 0$	Baryon number conserved
$S: -3 \rightarrow -1 + 0$	Strangeness number not conserved
$\therefore \quad \Delta S = -1 - -3 = +2$	Since allowed one for e.m interaction is $\Delta S = 0$

d) $\Lambda^\circ \rightarrow \pi^- + \pi^\circ$

$L: 0 \rightarrow 0 + 0$	Lepton number conserved
$B: 1 \rightarrow 0 + 0$	Baryon number not conserved
$S: -1 \rightarrow 0 + 0$	Since $\Delta S = 1$ and this being a weak interaction it is conserved.

Particle interactions and decays

In this section we discuss how the elementary particles are produced in laboratories and how are they measured. This is to study the structure and properties of elementary particles which is the ultimate aim of particle physics.

The study of atoms and molecules are relatively simple, since they are easily available non-violently. However, the elementary particles, most of which are unstable and do not exist in nature, must be created in violent collisions. For this we require a high energy beam of particles and a suitable target of elementary particles. The only strongly interacting, stable particle is the proton. This is easily available from hydrogen gas. This acts as the garget particles. To get reasonable density of protons researchers use liquid helium rather than gaseous hydrogen.

The incident beam must be accelerated to high energies for the collision to take place. The acceleration process takes place over a long time. so the incident beam particles must be stable. Usually electromagnetic fields are used to accelerate the particles, thus the particle must be charged. A best choice of charged and stable particle is again a proton. So protons are used as incident beam.

In laboratories the high energy incident beam (protons) is allowed to collide with high density target (protons).

The reaction occurs and other types of elementary particles are produced. The reaction is represented as

$$p + p \rightarrow \text{product particles.}$$

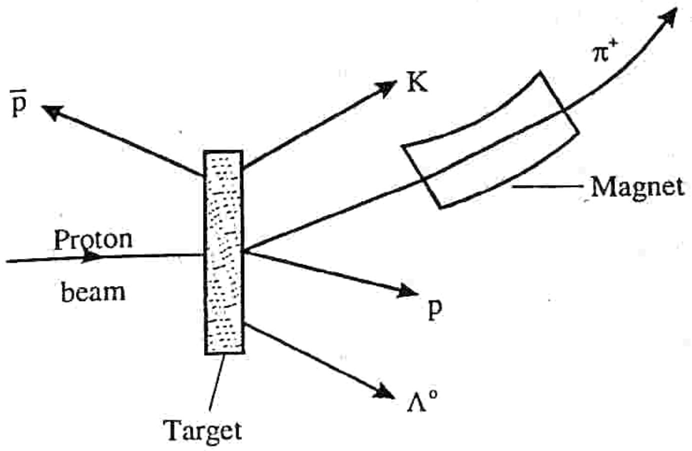


Figure 5.1: Proton - proton collision process

Among the product particles there may exist mesons, baryons, leptons, neutrinos etc. The magnet is used to separate out the desired particles. The conservation laws restrict the nature of product particles. To study one of the particles of product particles, we focus that particle and extract its beam out and made to fall on a second target. The second target might be tens of metres away. For the second reaction to take place the secondary beam must travel tens of metres. The time taken for this is $t = \frac{x}{v} = \frac{10\text{m}}{3\times10^8\text{m/s}} \simeq 10^{-7}\text{s}$. This shows that the particle that we selected must have a life time greater than 10^{-7}s. But most of the life time of elementary particle is less than 10^{-7}s. So a secondary reaction seems to be not possible. But relativistic speed of incident beam finds a solution to this. At relativistic speed time dilation effect comes into play. The life time of particle is measured in its rest frame (proper frame), while we are observing the particles flight in the laboratory frame. The time in the laboratory frame might be hundreds of times longer than the proper life time. Even if this proper life time of the particle is 10^{-10}s. It comes about greater than 10^{-7}s in our frame that makes the second reaction possible.

The reaction is

$$\pi + p \rightarrow \text{ particles}$$

$$K + p \rightarrow \text{particles}$$

This reactions enable us to study π and K particles.

Detecting particles

Observing the product particles in the reactions, which may involve dozens of high energy charged and uncharged particles, and their measurements is a challenge to experimentalists. What they do is a large number of detectors are placed surrounding the reaction area. The particles are recorded by these detectors, no matter what direction they travel after reaction. The particles produce visible tracks in the detector, so that their identity and direction of travel can be determined. The detector provides sufficient mass to stop the particles and measure their energy. A magnetic field is used to curve the charged particles. From the radius of curved path its momentum ($p=qBr$) and its energy $\left(\frac{q^2B^2r^2}{2m}\right)$ can be calculated. If the detector is a bubble chamber large number of tracks can be seen. A bubble chamber is a large tank filled with liquid hydrogen in which the passage of a charged particle cause microscopic bubbles resulting from the ionisation of the hydrogen atoms. The bubbles can be illuminated and photographed to reveal the tracks. A photograph of the bubble chamber tracks is given below in figure (5.2). Figure (5.3) is a diagram indicating the particles that participate in the reaction

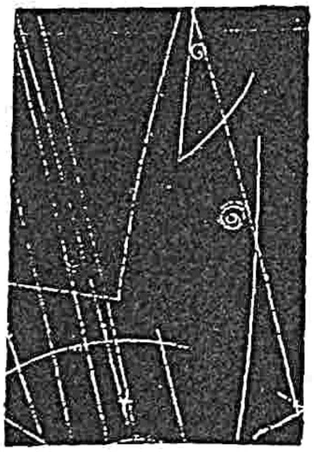


Figure 5.2: Bubble chamber photograph of particle reactions

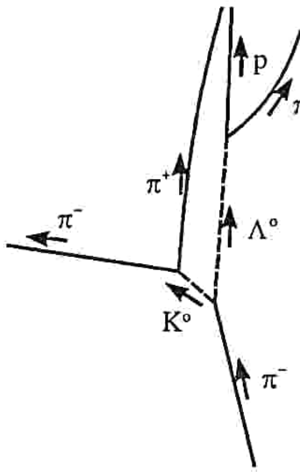


Figure 5.3: Directions of product particles

From careful analysis of the paths of the particles, the mass, momentum and energy of the particles can be deduced. The mean life of the particles can be calculated from the lengths of their tracks by knowing its speeds. Neutral particles leave no tracks. Since the neutrons are unstable and decay into charged particles leaving tracks in the bubble chamber. From these track lengths the mean lifetime of neutral particle can be estimated.

The above method of finding mean lifetime works well if the lifetime is of the order of 10^{-10} s or so. This can be extended down to about 10^{-16} s. But many of our particles have lifetimes of only 10^{-23} s, and a particle moving even at the speed of light the length of the track would be only about (x = vt) 10^{-15} m, the size of a nucleus. How can we measure such a lifetime? Further, how do we even know such a particle exists at all?

Consider the reaction

$$\pi + p \rightarrow \pi + p + x$$

where x is an unknown particle of lifetime 10^{-23} s, which decays into two pions according $x \rightarrow \pi + \pi$

How do we distinguish this reaction from the above reaction

$$\pi + p \rightarrow \pi + p + \pi + \pi$$

which leads to the same particles as actually observed in the laboratory.

Experimental evidence suggests that the two pions in this reaction may combine for an instant (10^{-23} s) to form an entity with all of the usual properties of a particle - a definite mass, charge, spin, lifetime etc. These states are known as resonance particles. The existence of the particles can be inferred indirectly.

Resonance particles

The word resonance implies something in tune or in harmony with something else. In nuclear physics the term resonance is taken from the phenomenon of neutron resonances.

A monoenergetic neutron beam from a reactor is allowed to fall on a target nuclei. Behind the target a neutron detector is placed. By measuring the neutron counts without and with the target present. We can get an idea of the extend to which neutrons of energy are absorbed by the target material.

Suppose we repeat this experiment at various neutron energies and represent the results as a plot of the absorption cross section σ_a of the nuclei in the target and neutron energy, we get a curve as shown in figure 5.4.

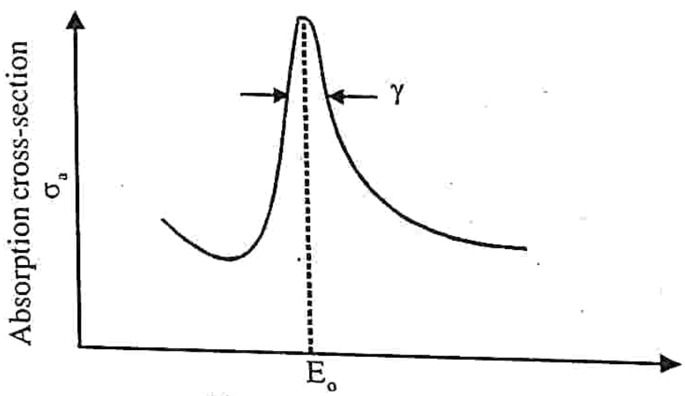


Figure 5.4

The peak at E_0 in σ_a is referred to as a neutron capture resonance. Neutrons of this particular energy E_0 are preferentially absorbed by the target nuclei, as compared to neutrons of other energies.

Now we come to the elastic scattering of pions by protons (just mentioned above) and the production of resonant particles. In the early 1950's Fermi was doing experiments on pion-proton, scattering cross section rises as shown in figure indicating the signature of resonance. After performing series of experiments in 1952 Fermi conclusively proved the existence of the phenomenon of resonance. When a pion is bombarded with a target nuclei proton, the target ejects a splatter of new just-born particles. However the lifetime of these particles is very low (10^{-23}s). The two particles (the incoming particle and the target nuclei) temporarily from a bound state like a Bohr atom. But this bound state is short lived. From the excited state the particle returns to normal state by decaying into some other particles through strong interaction. Formerly this bound state was called as resonant states. Later on it was found that mass, spin, magnetic moment etc. can be assigned to the resonant states. After that resonant states are renamed as resonant particles. Now we have large number of resonant particles.

Examples

1. When a proton is bombarded with a pion, at about 1238 MeV the resonant particle is formed (see figure below)

$$\pi^+ + p \rightarrow \Delta^{++}$$

$$\pi^- + p \rightarrow \Delta^0$$

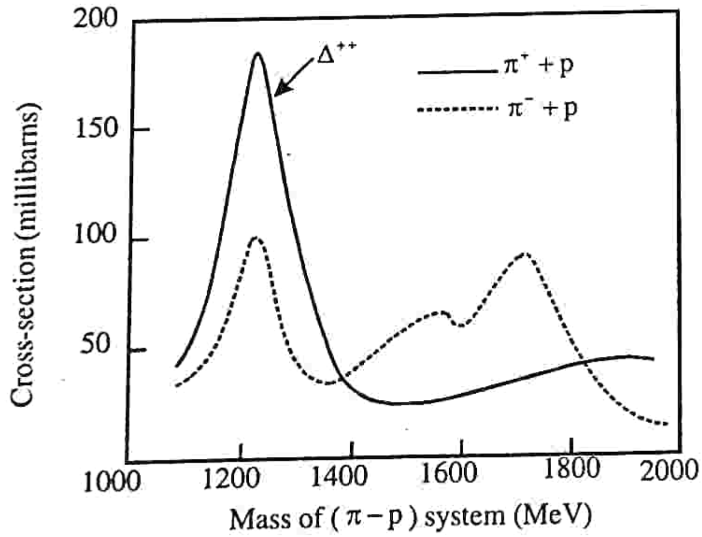


Figure 5.5

2. When a proton is bombarded with a kaon at about 1385 MeV the resonant particle Σ^* is formed

$$K^- + p \rightarrow \Sigma^{*+} + \pi^-$$

Σ^{*+} decays in 10^{-23} s into

$$\Sigma^{*+} \rightarrow \Lambda^\circ + \pi^+$$

Other possibility is

$$K^- + p \rightarrow \Sigma^{*-} + \pi^+$$

The resonant particle Σ^{*-} decays in 10^{-23} s into

$$\Sigma^{*-} \rightarrow \Lambda^\circ + \pi^-$$

Thus we see that $\Lambda^\circ\pi^+$ and $\Lambda^\circ\pi^-$ resonances are formed

3. Another resonant particle is the rho (ρ) meson. It is a two pions resonance particle. It can exist in three charge states ρ^+, ρ^- and ρ°. These are produced in high energy antiproton-proton annihilations.

$$p^- + p \rightarrow \rho + \pi + \pi$$

$$\rho^+ \rightarrow \pi^+ + \pi^\circ$$

$$\rho^- \rightarrow \pi^- + \pi^\circ$$

$$\rho^\circ \rightarrow \pi^+ + \pi^-$$

Resonances are divided into two categories. They are meson resonances and baryon resonances. Lepton cannot take part in the strong interactions.

Energetic of particle decays

While studying nuclear decays and reactions we used several conservation laws such as linear momentum, energy, angular momentum, charge, lepton number, baryon number, strangeness number etc. Many of these laws can be applied to the analysis of decays and reactions of the elementary particles. But there is a difference between the two. In the production of elementary particles, we require quite high energy for the incident particles. After collision the product particles (elementary particles) move with large velocities. So we have to use relativistic equations for momentum and energy. The production of elementary particles involve high energy, thus the name high energy physics.

The decays of elementary particles can be analysed in a way similar to the decays of nuclei, following the same two basic rules.

1. The Q-value of the decay is

$$Q = (m_i - m_f)c^2$$

Where $m_i c^2$ is the rest energy of the initial particle and $m_f c^2$ is the total rest energy of all the final product particles. It may be recalled that, the decay will occur only if Q is positive.

2. The available energy Q is shared as kinetic energy of the decay products in such a way as to conserve linear momentum. Remember that this kinetic energy is the relativistic one.

$$\text{i.e., } K = E - m_p c^2 = \sqrt{c^2 p_p^2 + m_p^2 c^4} - m_p c^2$$

where m_p is the rest mass of one of the product particles.

Example 9

Find the Q value of the decay

$$\Sigma^+ \to p + \pi^o, \quad m_\Sigma = 1189\frac{\text{MeV}}{c^2}, \quad m_p = 938\frac{\text{MeV}}{c^2} \text{ and } m_\pi = 135\text{MeV}/c^2$$

Solution

The Q-value is given by

$$Q = (m_i - m_f)c^2$$

$$Q = (m_\Sigma - m_p - m_\pi)c^2$$

$$Q = 1189 - 938 - 135 = 116\text{MeV}$$

Example 10

A neutral Kaon (K^o) with a kinetic energy of 276 MeV decays in flight into $\pi^+ + \pi^-$ which move off at equal angles with the original direction of the K^o. Find the energies and directions of motion of the π^+ and π^-. $m_{k^o} = 498\text{MeV}/c^2$, $m_{\pi^+} = 140\text{MeV}/c^2$

Solution

Using law of conservation of momentum.

Momentum before decay along x-direction

= Momentum after decay along x-direction

$$p_{K^\circ} = p_{\pi^+} \cos\theta + p_{\pi^-} \cos\theta \qquad ..... (1)$$

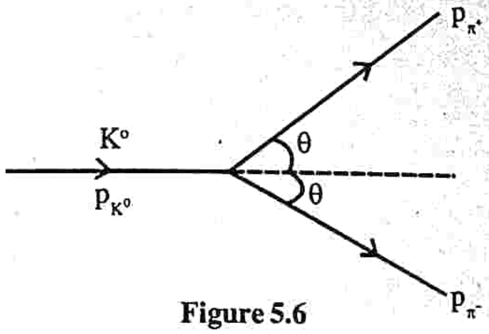


Figure 5.6

Along y-direction, we have

$$0 = p_{\pi^+} \sin\theta - p_{\pi^-} \sin\theta$$

or $$p_{\pi^+} = p_{\pi^-} \qquad ..... (2)$$

From the law of conservation of energy, we have

$$E_{K^\circ} = E_{\pi^+} + E_{\pi^-} \qquad ..... (3)$$

$$E_{K^\circ} = K_{K^\circ} + m_{K^\circ}c^2 = 276\text{MeV} + 498\text{MeV} = 774\text{MeV}$$

$$E_{\pi^+} = p_{\pi^+}^2 c^2 + m_{\pi^+}^2 c^4 \qquad ..... (4)$$

$$E_{\pi^-} = p_{\pi^-}^2 c^2 + m_{\pi^-}^2 c^4$$

since $p_{\pi^+} = p_{\pi^-}$, we get $E_{\pi^+} = E_{\pi^-}$

From eqn. (3), we get

$$E_{K^\circ} = 2E_{\pi^+}$$

or $$E_{\pi^+} = \frac{E_{K^\circ}}{2} = \frac{774}{2}\text{MeV} = 387\text{MeV}$$

From eqn.(4), we get

$$p_{\pi^+}^2 c^2 = E_{\pi^+}^2 - m_{\pi^+}^2 c^4$$

$$p_{\pi^+}c = \sqrt{E_{\pi^+}^2 - (m_{\pi^+}c^2)^2}$$

$$p_{\pi^+}c = \sqrt{(387)^2 - (140)^2} = 360.8\text{MeV}$$

Similarly $$p_{K^\circ}c = \sqrt{E_{K^\circ}^2 - (m_{K^\circ}c^2)^2}$$

$$p_{K^\circ}c = \sqrt{(774)^2 - (498)^2} = 592.5\text{ MeV}$$

Putting the values of p_{K° and p_{π^+} in eqn. (1), we have

$$\cos\theta = \frac{p_{K^\circ}}{2p_{\pi^+}} = \frac{592.5}{2\times 360.8} = 0.8210$$

$\therefore \qquad \theta = 34.81^\circ$

Example 11

Find the kinetic energy of the product particles in the given decay process.

$$\pi^+ \rightarrow \mu^+ + \upsilon_\mu$$

Assume that the decaying particle is at rest.

$$m_\pi = 140\frac{\text{MeV}}{c^2}, \quad m_\mu = 105.7\frac{\text{MeV}}{c^2}$$

Solution

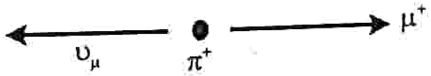


Figure 5.7

From the law of conservation of momentum we have

$$p_\upsilon = p_\mu$$

Energy conservation gives, $E_\pi = E_\mu + E_\upsilon$ ..... (1)

$$m_\pi c^2 = \sqrt{p_\mu^2 c^2 + (m_\mu c^2)^2} + p_\upsilon c$$

or $\qquad m_\pi c^2 - p_\upsilon c = \sqrt{p_\mu^2 c^2 + (m_\mu c^2)^2} \qquad (\because\ p_\mu = p_\upsilon)$

squaring on both sides, we get

$$(m_\pi c^2)^2 + p_\mu^2 c^2 - 2m_\pi p_\upsilon c^3 = p_\mu^2 c^2 + (m_\mu c^2)^2$$

or $\qquad (m_\pi c^2)^2 - 2m_\pi p_\upsilon c^3 = (m_\mu c^2)^2$

or $\qquad 2m_\pi p_\upsilon c^3 = (m_\pi c^2)^2 - (m_\mu c^2)^2$

$$p_\upsilon c = \frac{(m_\pi c^2)^2 - (m_\mu c^2)^2}{2m_\pi c^2}$$

$\therefore$

$$p_\upsilon c = \frac{(140)^2 - (105.7)^2}{2\times 140} = 30.1 \text{ MeV}$$

From eqn. (1), we have

$$E_\mu = E_\pi - E_\upsilon = E_\pi - p_\upsilon c$$

$$E_\mu = 140 - 30.1 = 109.9 \text{ MeV}$$

Using $E_\mu = K_\mu + m_\mu c^2$

$$\therefore \quad K_\mu = E_\mu - m_\mu c^2 = 109.9 - 105.6$$

$$K_\mu = 4.3 \text{ MeV}$$

Energetics of particle reactions

In particle reaction experiments we found that a beam of high energy particles collides with a target particle at rest results in the production of product particles. Here our aim is to study the kinetimatics of the reaction process. Since the kinetic energies of the particles are usually high, we must go for relativistic formulae. To analyse the reaction process we need some relationships such as Q – value of the reaction and threshold energy to initiate the reaction. Here we are going to derive that.

Consider the reaction:

$$m_1 + m_2 \rightarrow m_3 + m_4 + m_5 + \ldots\ldots$$

m's stand for masses as well as for particles. Here m_1 is the incident particle which has total energy E_1 and kinetic energy $K_1 = E_1 - m_1c^2$ and momentum

$$p_1 c = \sqrt{E_1^2 - m_1^2c^4}, \quad (\because \; E_1 = \sqrt{p_1^2 c^2 + m_1^2 c^4})$$

The target particle m_2 is at rest, hence having only rest energy m_2c^2. Remember that all are measured in the lab frame of reference.

The Q-value of the reaction is

$$Q = (m_i - m_f)c^2 = \left[(m_1 + m_2) - (m_3 + m_4 + m_5 + \ldots\ldots)\right]c^2$$

If Q is positive, rest energy is turned into kinetic energy, so that the product particles m_3, m_4, m_5, ... have m are combined kinetic energy than the initial particles m_1 and m_2. If Q is negative some of the initial kinetic energy of m_1 is turned into rest energy.

Threshold energy

When the Q-value is negative, there is a minimum kinetic energy that m_1 must have in order to initiate the reaction is called threshold energy. In the case of non-relativistic nuclear reaction we found that the threshold kinetic energy $K_{th} = -Q\left[1+\frac{m(x)}{m(X)}\right]$ in the reaction process $x + X \rightarrow y + Y$. This K_{th} is larger than Q. The value is the energy necessary to create the additional mass of the product particles, as well as to impart sufficient kinetic to the product particles to conserve momentum.

Expression for threshold energy

A particle of mass m_1 moving with momentum p_1 and energy E_1 collides a particle of mass m_2 at rest having energy $E_2 = m_2c^2$. After collision large number of particles of masses m_3, m_4, m_5,..... are produced. We assume that all these particles move along a straight line with the same speed together. At threshold this is the most efficient way to provide momentum to the final particles.

Let M and p_M be the total mass and total momentum of the product particles respectively.

According to law of conservation of energy

$$E_1 + E_2 = E_M$$

where E_M is the total energy of the product particles.

i.e., $$\sqrt{(p_1c)^2 + (m_1c^2)^2} + m_2c^2 = \sqrt{(p_Mc)^2 + (m_Mc^2)^2} \quad \text{..... (1)}$$

According to law of conservation of momentum

We have $p_1 = p_M$

Thus eqn. (1) becomes

$$\sqrt{(p_1c)^2 + (m_1c^2)^2} + m_2c^2 = \sqrt{(p_1c)^2 + (Mc^2)^2}$$

$$(\because p_M = p_1 \text{ and } m_M = M)$$

squaring on both sides, yields

$$(p_1c)^2 + (m_1c^2)^2 + (m_2c^2)^2 + 2m_2c^2\sqrt{(p_1c)^2 + (m_1c^2)^2}$$

$$= (p_1c)^2 + (Mc^2)^2$$

or $\quad (m_1c^2)^2 + (m_2c^2)^2 + 2m_2c^2\sqrt{(p_1c)^2 + (m_1c^2)^2} = (Mc^2)^2$

i.e., $\quad = \sqrt{(p_1c)^2 + (m_1c^2)^2} = \dfrac{(Mc^2)^2 - (m_1c^2)^2 - (m_2c^2)^2}{2m_2c^2}$

The threshold kinetic energy of m_1 is

$$K_{th} = E_1 - m_1c^2$$

$$K_{th} = \sqrt{(p_1c)^2 + (m_1c^2)^2} - m_1c^2$$

$$K_{th} = \frac{(Mc^2)^2 - (m_1c^2)^2 - (m_2c^2)^2}{2m_2c^2} - m_1c^2$$

$$K_{th} = \frac{(Mc^2)^2 - (m_1c^2)^2 - (m_2c^2)^2 - 2m_1m_2c^4}{2m_2c^2}$$

$$K_{th} = \frac{(Mc^2)^2 - (m_1c^2 + m_2c^2)^2}{2m_2c^2}$$

$$K_{th} = \frac{(Mc^2 + m_1c^2 + m_2c^2)(Mc^2 - m_1c^2 - m_2c^2)}{2m_2c^2}$$

(Used $a^2 - b^2 = (a+b)(a-b)$)

But $Q = m_1c^2 + m_2c^2 - Mc^2$

$$K_{th} = \frac{-Q(Mc^2 + m_1c^2 + m_2c^2)}{2m_2c^2}$$

or $$K_{th} = \frac{-Q[m_1 + m_2 + m_3 + m_4 + m_5 ...]}{2m_2}$$

i.e. $$K_{th} = \frac{-Q \times \text{total mass of all particles involved in reaction}}{2 \times \text{mass of target particle}}$$

This is the expression for threshold kinetic energy.

Consider the reaction

$$x + X \rightarrow y + Y$$

$$K_{th} = \frac{-Q[m(x) + m(X) + m(y) + m(Y)}{2m(X)}$$

In the non-relativistic case, all kinetic energies are very small compared to rest energies, so that the total rest energy in the reaction does not change.

i.e., $$m(x) + m(X) = m(y) + m(Y)$$

so the above equation becomes

$$K_{th} = -\frac{Q}{2}\frac{[2m(x) + 2m(X)]}{m(X)}$$

or $$K_{th} = -Q\left[1 + \frac{m(x)}{m(X)}\right]$$

This is our expression for non-relativistic threshold kinetic energy. This shows that in the limit of low speeds, the relativistic threshold kinetic energy formula reduces to the non-relativistic formula.

Finally we estimate the efficiency of the reactions. Efficiency in the sense that how much initial energy that we supply actually goes into producing the reaction products (rest energy of the product particles) and how much is wasted as the kinetic energies of the reaction products. Suppose 400 MeV of kinetic energy is given to a reaction to produce 200 MeV of rest energy of the product particles, then efficiency

$$= \frac{200 \text{ MeV}}{400 \text{ MeV}} = \frac{1}{2} = 50\%$$

For example to produce a particle of 50 GeV rest energy, suppose we require 1250 GeV of initial kinetic energy. Then

$$\text{efficiency} = \frac{50 \text{ GeV}}{1250 \text{ GeV}} = 0.04 = 4\%$$

This show that efficiency is only 4%, where 96% of initial kinetic energy must go to the kinetic energies of particles. This is obviously an uncomfortable situation for particle physicists. This is because if they try to produce more massive particles, they must build more powerful accelerators.

To overcome this difficulty, we do the experiments in C M frame. In this frame two particles with equal and opposite momentum collide head-on. After collision particles produced are at rest in the C M frame. That means no initial kinetic energy is transferred to the kinetic energy of the product particles. Thus the efficiency of this reaction is 100%. For example two protons of 25 GeV kinetic energy collide head-on the total energy after collision is 50 GeV. This can produce a particle of 50 GeV rest energy. This is the mechanism used in large hadron collider (LHC) that we already discussed. To have more clarity about efficiency see examples 12 and 13.

Example 12

Find the threshold kinetic energy and efficiency of the reaction.

$$p + p \rightarrow p + p + \pi^o$$

$$m_p = 938\frac{\text{MeV}}{c^2} \qquad m_\pi = 135\frac{\text{MeV}}{c^2}$$

Solution

$$Q = (m_i - m_f)c^2 = [m_p + m_p - (m_p + m_p + m_\pi)]c^2$$

$$Q = -m_\pi c^2 = -135\text{MeV}$$

Threshold kinetic energy

$$K_{th} = -Q\frac{\text{Total mass of all particles involved}}{2 \times \text{mass of the target}}$$

$$K_{th} = -\frac{Q\ (4m_p + m_\pi)}{2m_p}$$

$$K_{th} = \frac{--135\,(4\times 938+135)}{2\times 938}$$

$$K_{th} = 279.7\text{MeV}$$

$$\text{Efficiency} = \frac{\text{Rest energy of } \pi^{o} \text{ produced}}{\text{Threshold kinetic energy}}$$

$$= \frac{135}{279.7} = 0.4820 = 48.2\%$$

Example 13

Calculate the threshold kinetic energy and efficiency of the reaction

$$p + p \rightarrow p + p + \overline{p} + \overline{p}$$

Solution

$$Q = (m_i - m_f)c^2$$

$$Q = [2m_p - (2m_p + 2\overline{m}_p)]c^2$$

$$Q = -2\overline{m}_p c^2$$

The rest energy of the antiproton ($\overline{p}$) is the same as that of the proton

$$\therefore \quad Q = -2\overline{m}_p c^2$$

Threshold kinetic energy:

$$K_{th} = \frac{-Q \text{ Total mass of all products involved}}{2\times \text{mass of the target}}$$

$$K_{th} = --2m_p c^2 \, \frac{6m_p c^2}{2m_p c^2} = 6m_p c^2$$

$$K_{th} = 6\times 938\text{MeV} = 5628\text{MeV}$$

$$\text{Efficiency} = \frac{\text{Rest energy of particle produced}}{\text{Threshold kinetic energy}}$$

$$= \frac{2m_p c^2}{6m_p c^2} = \frac{1}{3} = 33.33\%$$

Example 14

Find the threshold kinetic energy for the reaction in the lab frame.

$$\pi^- + p \rightarrow \Sigma^o + K^o$$

$$m_{\pi^-} = 140\ \frac{MeV}{c^2},\quad m_p = 938\ \frac{MeV}{c^2},\quad m_{\Sigma^o} = 1192\ \frac{MeV}{c^2}\ \text{and}\ m_{K^o} = 498\ \frac{MeV}{c^2}$$

Solution

$$Q = (m_i - m_f)c^2 = (m_\pi + m_p - m_\Sigma - m_K)c^2$$

$$Q = (140 + 938 - 1192 - 498)\text{MeV}$$

$$Q = -612\ \text{MeV}$$

$$K_{th} = -Q\frac{[m_\pi + m_p + m_\Sigma + m_K]}{2m_p}$$

$$K_{th} = --612\ \frac{[140 + 938 + 1192 + 498]}{2\times 938}$$

$$K_{th} = 902.99\ \text{MeV}$$

The quark model

Quarks

What are the basic building blocks of matter? We had been trying to answer this question for a long time. In the last session we arrived at a conclusion that the elementary particles discussed are the basic building blocks of matter. Electrons, protons, neutrons, pions, kaons, photons, gravitons, resonant particles etc. were termed as fundamental or elementary particles. The developments and researches in the theoretical physics predicted particles which are more fundamental than elementary particles discussed in the last session. These particles are named as quarks. In 1964 Murry Gell-mann and independently G zweig introduced the idea of the basic unit named quarks to explain the internal constitution of baryons and mesons. Zweig called his particles 'ace' but it was the same as the quark of Gell-mann. The quark model was not a theoreticians mathematical artifice. It was actually being demanded by experimentalist and their experiments. Upto about 50 years ago it was thought that protons and neutrons were elementary particles, but experiments in which protons were collided with other protons and electrons at high speeds indicated that they were in fact made up of smaller particles. These particles were named as quarks. Gell-mann taken this name from a song in the novel 'Finnigans wake' written by James Joyce. The song goes like this:

Three quarks for muster mark !

Sure he hasn't got much of a bark

And sure any he has its all beside the mark.

Joyce used the term 'quark' for the cry of a frog (crok- crok)

In the quark model of Gellmann he developed theoretically the following attributes to the quarks.

(i) All the three quarks (u, d and s) have fractional charges.

$$\text{up quark has a charge } \frac{2}{3}e$$

$$\text{down quark has a charge } -\frac{1}{3}e$$

$$\text{strange quark has a charge } -\frac{1}{3}e$$

(ii) All quarks have spin $\frac{1}{2}\hbar$

i.e., quarks are fermions

(iii) The antiparticle of quarks are called antiquarks. $\overline{u}$, $\overline{d}$ and $\overline{s}$ are the antiquarks of up, down and strange quarks respectively.

(iv) All baryons are made up of three quarks. For example proton (baryon) is made up of u, u and d quarks.

i.e., $u + u + d = p$

$$\frac{2}{3}e + \frac{2}{3}e - \frac{1}{3}e = e$$

So charges are conserved.

A neutron is made up of u, d, d quarks

i.e., $u + d + d = n$

$$\frac{2}{3}e - \frac{1}{3}e - \frac{1}{3}e = 0$$

Similarly an antiproton is made up of $\bar{u}, \bar{u}$ and $\bar{d}$

i.e., $\bar{u}+\bar{u}+\bar{d}=\bar{p}$

$$-\frac{2}{3}e+\frac{-2}{3}e+\frac{1}{3}e=-e$$

An antineutron is made up of $\bar{u}$, $\bar{d}$ and $\bar{d}$

i.e., $\bar{u}+\bar{d}+\bar{d}=\bar{n}$

$$\frac{-2}{3}e+\frac{1}{3}e+\frac{1}{3}e=0$$

V. All mesons are made of one quark and one antiquark.

Example

1. $\pi^{+}=u+\bar{d}$
2. $K^{+}=u+\bar{s}$

We can easily check the conservation of charges on both sides.

Gellmanns quarks and their attributes

Name	Symbol	Rest mass in MeV	Charge in units of e	spin $\hbar$
Up	u	310	$\frac{2}{3}$	$\frac{1}{2}$
Down	d	310	$-\frac{1}{3}$	$\frac{1}{2}$
Strange	s	505	$\frac{-1}{3}$	$\frac{1}{2}$

Using the above six rules Gellmann could be readily explained all the known particles in the mid sixties. By using quark model Gell-mann formulated a method of classifying elementary particles that enabled him to predict omega ($\bar{\Omega}$) particle which is made of three s quarks

i.e., $\bar{\Omega}=s+s+s$

Later $\bar{\Omega}$ particles was experimentally detected, it was a great truimph for Gell-mann and his quarkmodel. For this Gellmann was awarded the Nobel prize in physics in 1969.

Flavour of quarks

In addition to u,d, and s quarks three more quarks were predicted and the signature of their existence were detected. They are named as charm (c), top (t) and bottom (b) quarks. Earlier the t and b quarks used to be called truth and beauty respectively, but some how, the mundane labels top and bottom have replaced them. Now in the quark family there are six members and their corresponding antiparticles. One can either think of it as six different quarks or six dfferent states of the same particle just as the neutron and the proton can be regarded as two different states of the nucleon. In the latter case, one refers to the six different quarks states as having different flavours. Considering quarks and antiquarks together one can say there are 12 flavours of quark and antiquark.

Name	Symbol	Restmass in MeV	Charge in units of e	Spin $\hbar$
Charm	c	1500	$\frac{2}{3}$	$\frac{1}{2}$
Top	t	177000	$\frac{2}{3}$	$\frac{1}{2}$
Bottom	b	5000	$-\frac{1}{3}$	$\frac{1}{2}$

Colour of quarks

Gell-manns original quark model predicted only three quarks namely u, d, and s. Even at that time, a serious difficulty was noticed in the Gell-mann's model. To understand this let us consider the omega (Ω^-) hyperon. It is made of three s quarks

i.e., $\Omega^- = s+s+s$

The spin $\frac{3}{2}\hbar$ of Ω^- is easily understood by noting that it has three quarks (sss), each of which has a spin of $\frac{1}{2}\hbar$. Similarly the charge of Ω^- is negative since each s has a charge $-\frac{1}{3}e$. But then quarks being fermions how can one have more than one quark in the same spin state. According to Paulis exclusion principle no two fermions can be in the same state. In other words quark model is violating the Paulis exclusion principle. This was the problem but a solution was quickly found borrowing upon earlier experience in atomic and nuclear physics. The trick was to introduce another property for the quarks so that the three s quarks in Ω^-, while all being in the spin $\frac{1}{2}\hbar$ state differ with respect to the property we assign to them. Let us call this new property C and let us suppose that C can take on three values C_1, C_2 and C_3, Just as spin $\frac{1}{2}\hbar$ can take values $\frac{1}{2}\hbar$ and $-\frac{1}{2}\hbar$. With the aid of C we can now stipulate that the three s quarks in Ω^- should occupy the states $\left(\frac{1}{2}\hbar, C_1\right)$, $\left(\frac{1}{2}\hbar, C_2\right)$ and $\left(\frac{1}{2}\hbar, C_3\right)$. Obviously the states of s are different.

The idea of invoking such a new property was first proposed by Oscar green berg and independently by Nambu who called this new property colour. According to Nambu each quark comes in three colours. Red (R), green (G) and blue (B). Thus according to this idea in Ω^- one of the quarks is red, the second one is green and the third one is blue. What about the antiquarks? What are their colours. Nambu said that the antiquarks have anticolours. i.e., antired $(\bar{R})$, antigreen $(\bar{G})$ and anti blue $(\bar{B})$.

It must be noted that this colour has nothing to do with colour in every day parlance. This new colour property was assigned to quark to maintain the status quo of the well established (experimentally) Paulis exclusion principle. According to the colour property assigned to quarks, all three quarks in a baryon have different colours which satisfies the Paulis exclusion principle. Such a combination can be thought of as while by analogy with the way red, green and blue light combine to make white (colourless). Similarly an antibaryon consists of an antired, an anti green and an antiblue quark. A meson consists of a quark of one colour and an anti quark of the corresponding anti colour, which has the effect of cancelling out the colour. The results is that hadrons (baryons and mesons) and antihandrons are colourless.

Note: To have some idea about anti colours in analogy with the colours that one can perceive with the human eyes go through the following.

Since all baryons made up of three quarks, are colour less, we must have three quarks with different colours

$$R + G + B = W \text{ (white)} \quad .....(1)$$

All mesons, made up of a quark and an antiquark, are colour less. We must have

$$R + \bar{R} = W \quad .....(2)$$

comparing equation (1) and (2) we have $\bar{R} = G + B$

i.e., combing green and blue, we get antired. Combining blue and green we know that we get cyan (peacock blue)

It means that antired is nothing but cyan similarly we have

$$R + G + B = W$$

and $$G + \bar{G} = W$$

Comparing $$\bar{G} = R + B$$

i.e., combining red and blue, we get antigreen. Red and blue combines to magenta. It means that anti green is nothing but magenta.

Using $$R + G + B = W$$

and $$B + \bar{B} = W$$

comparing $$\bar{B} = R + G$$

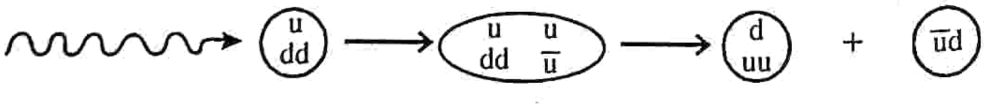
Antiblue is the combination red and green. Combining red and green we get yellow it means that antiblue is nothing but yellow.

Quark confinement

When the quarks were first proposed, the first question people asked was how can we see quarks. After that people were in the hot pursuit of conducting experiments for the detection of free quarks. None could be successful. Finally they concluded that quarks were permanently imprisoned inside. This is the idea of quark confinement.

With sufficient energy one can tear an atom apart and free the electrons and nucleus inside. With even more energy one could tear a nucleus into its constituent neutrons and protons. But with still higher energy one could not manage to knock out a quark from a baryon or a meson. When one hits a baryon very very hard something must happen. It does so but quarks manage to stay inside and never comes out singly even if others are produced. When enough energy is given, instead of a quark breaking free from the others in a hadron, the excess energy goes into producing a quark-antiquark pair. this results in a meson that does escape. For example when an energetic gamma ray photon impinges on a neutron (udd) and causes a $u\bar{u}$ quark-antiquark pair to come into being. The quarks $udd + u\bar{u}$ then rearrange themselves into a proton (uud) and negatively charged pion $(\bar{u}d)$. The net reaction is as follows

$$\gamma + n \rightarrow p + \pi^-$$



The quark pair is like a chest expander whose spring is infinitely strong. Consider a chest expander spring. The more one pulls, the harder it is to expand the spring. The more one pulls, the harder it is to expand the spring further. Let us consider the other extreme. If the spring is laid loosely on the ground the two ends can be easily and independently pushed around. This analogy carriers over beautifully into the world of quarks. The spring that binds two quark is colour force and is like the chest expander. The more one increases the distance between two quarks, the harder it becomes to separate them further.

Quarkonium

We found that baryons consist of three quarks. Technically speaking it is a three body quantum mechanical system. As there is no mathematical tool to tackle a three body problem, it is very difficult to extract the properties and interactions of quarks forming baryons. However we can learn a little bit about the interactions of quarks from examining the properties of two body systems, especially quark-anti quark pairs in mesons.

We know that mesons are formed by the combination of quarks and antiquarks. The binding energies of quarks in mesons are very large (hundreds of MeV), so the quark-antiquark pairs of the light quarks (u, d, s) must be treated relativistically. This is because the binding energies and rest energies of light quarks are roughly the same. However, for the massive quarks (c, b, t) the binding energies are small compared to rest energies, so we can use non-relativistic methods for the analysis.

The bound quark-antiquark pair is called quarkonium. We can study the properties of quarkonium in analogy with the well studied positronium. The bound state of positron electron pair is called positronium. The positronium structure is very much similar to quarkonium. In positronium, positron and electron each orbit about their centre of mass. It is very much like a hydrogen atom. Hence we can label the states of positronium with orbital angular momentum quantum number L and spin quantum number S.

The total orbital angular momentum quantum number $L = 0$ for s states and $L = 1$ for p states. If the two particles are parallel their total spin $S = 1$, for antiparallel $s = 0$. The system can exist with different radial wave functions that we can label it by principal quantum numbers n = 1, 2, 3.....

These designations can as such be applied to quarkonium. It has been found that $c\bar{c}$ quarkonium structure is very much similar to positronium. The lowest $S = 1$, $L = 0$, $c\bar{c}$ state is the J/ψ meson. This meson was discovered in the year 1974 and could be explained on the basis of quark structure. Unfortunately the structure of

$b\bar{b}$ quarkonium resulting in γ-meson has not been completely verified in experiments. The only thing that we know is all quarkonium structures similar to positronium.

The knowledge of the excited states of quarkonium enables us to guess a model for their potential energy of interaction. There are several models available among the researchers of quark-gluon plasma. One simple model of potential energy is

$$U = \frac{a}{r} + br$$

By using potential energy, we can solve the Schrodinger equation to get energies of different states. The values of a and b are chosen in such a way that the energy that we obtained from solving Schrodinger equation must tally with experimental result. The constant b turns out to be $\text{GeV}(\text{fm})^{-1}$. This shows that large amount of energy is required to separate two quarks apart. To separate quarks in a meson even to a atom sized distance $(10^{-10}\text{m} = 10^5\text{fm})$, we require about 10^5 GeV energy. This energy is get to be achieved in accelerators. This is the reason why we didn't see free quarks in laboratories. Now we believe that one day this energy will be produced in accelerators so that we can see free quarks which are the basic building blocks of the universe.

The standard model

Introduction

Until the 1930's all natural phenomena were presumed to have their origin in just two basic forces - they were gravitational and electromagnetism. Both were described by classical fields that permeated all space. These fields extended out to infinity from well defined sources, mass in one case and charge in the other. This rule over the physical universe seemed securely established. As atomic and subatomic phenomena were explored, it became apparent that two completely novel forces had to be added to this list, they were the weak and strong force. The strong force was necessary inorder to understand how the nucleus is held together, protons bound together in tight nuclear ball (10^{-15}m size) must be subject to a force much stronger than electromagnetism to prevent their flying apart. The weak force was invoked to understand the transmutation of a neutron in the nucleus into a proton during the particularly slow form of radioactive decay known as beta decay.

Since neither the weak force nor strong force is directly observed in the microscopic world, both must be very short range relative to the more familiar gravitational and electromagnetic forces. Furthermore, the relative strengths of the forces associated with all four interactions are different. $(F_s : F_e : F_w : F_g = 1 : 10^{-2} : 10^{-5} : 10^{-38})$. It is therefore not too surprising that for a very long period these interactions were thought to be quite separate. Inspite of this, there had always been a lingering suspicion and hope that in some miraculous fashion all four were simply manifestations of one source or principle and could therefore be described by a single unified theory.

The first step towards unification was begun in 1967 with the development of the electroweak theory (EW) by Stephen Weinberg and Abdus Salam. In this theory, the weak and electromagnetic interactions are regarded as separate aspects of the same force - the electroweak force, just as electric and magnetic forces are distinct but part of a single phenomenon, electromagnetism. The theory predicted the existence of vector bosons ($W^{\pm}, Z^{o}$) were experimentally detected which provided a confirmation to the electroweak force. After this we have only three basic forces strong, electroweak and gravitational. The next aim of the scientific community was to unify strong and electroweak forces under the name standard model.

According to this model the strong force that binds nucleons into nuclei and is mediated by pion exchange is the external manifestation of the colour force between quarks in the nucleons that is mediated by gluons. That is the strong force between quarks is carried by an exchanged particles called the gluon, which provides the, glue that binds the quarks together in mesons and baryons. There are totally eight different gluons in this model. A theory known as Quantum Chromo Dynamics (QCD) describes the interactions of quarks and exchange of gluons. Like the quarks, gluons have not been observed experimentally, but there is indirect evidence of their existence from a variety of experiments.

The Standard Model (SM)

The standard model is the amalgamation of strong interaction and electroweak interaction. The standard model sees the world as built up of two sets of particles quarks and leptons and the field particles. There are six quarks and 6 leptons and their antiparticles plus the field particles (photons, 3 vector bosons (W^+, W^- and Z^o) and eight gluons). The quarks are described by QCD and leptons by EW theory. The unified theory of these three interactions (strong, weak and electromagnetism) is called the standard model. The gravitational interaction does not come under the standard model.

Though this model is not fully successful, it is on the way to its success. The main drawback of this model that important elements of the model have to be inserted arbitrarily. The model require us to measure the masses of leptons and quarks experimentally. Inorder for the standard model of quarks and leptons to be mathematically consistent, the Scottish physicist Peter Higgs showed that, a field now called the Higgs field must exist everywhere in space. When particles interact with Higgs field they acquire their characteristic mass. The stronger the interaction the greater the mass, we can think of the Higgs field as exerting a kind of viscous drag on the particles that move through it, this drag appears as inertia, the defining property of mass. As with the other, a particle here called Higgs boson mediate the action of Higgs field.

Discovery of Higgs bosons and knowing its mass and behaviour predicted by standard model would be major step in validating the standard model. For this we constructed a very powerful accelerator at CERN in Switzerland, Genevà called Large Hadron Collider (LHC). We already discussed about LHC in detail. LHC is currently searching for the evidence of the Higgs particles by colliding beams of protons at an energy of 7000 GeV. The physics community is eagerly looking at the observation results going to be revealed.

The second drawback of the standard model is that it is based on massless neutrinos. But experiments revealed that neutrinos are massive even though very small (mass of electroneutrino is 2 eV). So the standard model must be extended to include non zero neutrino masses and the rules for conservation of lepton number must be modified to allow one type of neutrino into another called neutrino oscillation.

Neutrino Oscillation

Measurements of the flux of neutrinos reaching the Earth from the Sun, produced in the fusion reactions, revealed that there is a large defect. The intensity of electroneutrinos observed on Earth is only about 1/3 of what is predicted based on models of how fusion reactions occur in the sun's interior. Recent measurements revealed that the intensity of all neutrions including muon and tau neutrions are in agreement with the predicted rate. At the same time sun produces only electron neutrinos. This is because the reacting particles in the solar interior are not sufficiently energetic to produce muon and tau neutrinos. Then how they come in our atmosphere. This mystery has been explained by proposing that the electron neutrinos are produced in the solar interior at the expected rate, but that during journey from the sun to the Earth, the purely electron neutrinos becomes a mixture of roughly equal parts of electron, muon and tau neutrinos. This explains why only 1/3 of electron neutrinos are present on Earth. This phenomenon of converting electron neutrinos into muon and tau neutrinos is called neutrino oscillation.

The third drawback of the standard model is that the fundamental particles and forces are quarks and eight gluons. They have not observed so far. Furthermore nobody so far has been able to derive the details of strong force emerging from colour quarks.

The unified theory explaining the four interactions is called Grand Unification Theory (GUT).

IMPORTANT FORMULAE

1. Basic forces : Strong, electromagnetic, weak and gravitational
2. Field particles : Gluons, photon, vector bosons (W^+, W^- and Z^o) and graviton
3. Leptons : e^-, υ_e, μ^-, υ_μ, τ^- and υ_τ
4. Mesons : $\pi^+, \pi^-, \pi^0, K^+, K^-, K^0, \eta, \rho^+, \rho^-, \eta'$.......
5. Baryons : $p, n, \Lambda^0, \Sigma^+, \Sigma^-, \Sigma^0, \Xi^-, \Xi^0, \Omega^-$.........
6. Conservation of lepton number : In any process L_e, L_μ and L_τ remain constant
7. Conservation of baryon number : In any process remains B constant
8. Conservation of strangeness : In strong and electromagnetic process S remains constant, in weak process $\Delta S = 0, \pm 1$
9. Q-value in reactions, $Q = (m_i - m_f)c^2$
10. Threshold kinetic energy in reactions, $K_{th} = \dfrac{-Q(m_1 + m_2 + m_3 + ...)}{2m_2}$
11. Quarks : u, d, c, s, t, b.
12. In high energy physics, relativistic momentum is conserved also total energy $E = K + mc^2$ is also conserved.

    Where $E = \sqrt{p^2c^2 + m^2c^4}$ and mc^2 is the rest energy.

UNIVERSITY MODEL QUESTIONS

Section A

(*Answer questions in about* **two** *or* **three** *sentences*)

Short answer type questions

1. What are elementary particles?
2. Name the four basic forces in nature?
3. Which forces are to be considered while determining the stability and structure of nuclei?
4. How will you distinguish between weak force and strong force?
5. Distinguish between particles and antiparticles?
6. What is antihydrogen atom?
7. Name the three types of neutrinos?
8. Do all strongly interacting particles also feel weak interaction?
9. What are Fermions and Bosons?
10. Classify the elementary particles on the basis of mass.

11. What are baryons? Name three of them?
12. What are mesons? Name three of them?
13. What are leptons? Give their names?
14. What are the types of interactions that leptons take part?
15. What are the types of interactions that baryons take part?
16. Give an example for lepton number conservation?
17. Give an example for baryon number conservation?
18. Give an examples for strangeness conservation?
19. In particle interactions and decays the beam particle and target particle are protons. Why?
20. What are resonance particles?
21. Give an example for the formation of resonance particle?
22. In high energy particle physics, the neutral particles produced in reactions leave no tracks in the bubble chamber, then how will we estimate their lifetime?
23. What is meant by threshold energy in high energy particle reactions?
24. Write down an expression for threshold kinetic energy in particular reactions and explain the symbols used?
25. What is meant by efficiency of a nuclear particle reaction?
26. How do we improve the efficiency of particle reactions?
27. In high energy particle physics, lab frame or CM frame which is more efficient to conduct experiments?
28. What are quarks?
29. Protons and neutrons are made up of quarks. Explain?
30. What is meant by flavour of quarks?
31. Give the names of flavours of quarks?
32. What is meant by colour of quarks?
33. What is standard model?
34. What are Higgs bosons?
35. What is electroweak theory?
36. What are messenger or field particles?
37. Write down the names of all field particles?
38. Write down the decay of a positively charged pion?
39. Write down the decay of a negatively charged pion?
40. What is meant by quark confinement?
41. What is quantum chromodynamics?
42. What is quarkonium?
43. Which are the mediating particles of electroweak force?
44. What is graviton?
45. What is neutrino oscillation?

Section B

(Answer questions in a **paragraph** *of about half a page to one page)*

Paragraph / Problem type questions

1. Distinguish between gravitational force and electromagnetism?
2. What is strong force? Write down its properties?
3. What is weak force? Write down its properties?
4. Neutrinos are not a part of ordinary matter, then how will you distinguish between neutrino and an atineutrino?
5. Distinguish between four basic forces ?
6. Write a brief note on three member families of particles?
7. What is lepton number conservation?
8. What is baryon number conservation?
9. What is strangeness number conservation?
10. The mean life time of most of the product particles is about 10^{-10} s in particle reactions. Then how it is possible to produce a secondary collision where the second target is at a distance of 10m away from the first target
11. How do we detect product particles in particles reactions?
12. How will we calculate the mean life of product particles produced in high energy particle decay?
13. How can we measure the mean life of a particle of the order of 10^{-23} s produced in particle reactions?
14. Explain what is meant by resonance and resonance particles?
15. What are the two basic rules that can be applied in the decay of elementary particles produced in high energy reactions?
16. Show that in the non-relativistic limit, the relativistic expression for threshold kinetic energy becomes non-relativistics threshold kinetic energy?
17. Why quarks have fractional charges? Substantiate with two examples.
18. Explain the emergence of colour of quarks?
19. Explain briefly the standard model?
20. What are the drawbacks of standard model?
21. Explain the origin of neutrino oscillation?
22. Which of the following reactions can occur? State the conservation principles violated by the others.

    a) $p+p \rightarrow n+p+\pi^{+}$ b) $p+p \rightarrow p+\Lambda^{o}+\Sigma^{+}$

    c) $e^{-}+e^{+} \rightarrow \mu^{+}+\pi^{-}$ d) $p+p \rightarrow \pi^{+}+K^{o}+\Lambda^{o}$

    [a) possible, b) not possible, c) not possible, d) possible]
23. Check whether the given reaction is possible or not

a) $K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$ b) $K^+ \rightarrow \mu^+ + \upsilon$ [a) not possible, b) not possible]

24. Which one is a possible reaction

a) $\pi^- + p \rightarrow \Lambda^\circ + K^\circ$ b) $K^- + p \rightarrow \Sigma^+ + \pi^-$ [a) possible, b) possible]

25. Which quarks make up the negative pion? [$\bar{u}d$]

26. What particle corresponds to the quark composition uus [Σ^+]

27. Can a Λ particle decay into π^+ and π^- meson [No]

28. The quantum numbers of three quarks are tabulated below

	Charge	B. No.	Strangeness
q_1	$\frac{2}{3}e$	$\frac{1}{3}$	0
q_2	$-\frac{1}{3}e$	$\frac{1}{3}$	0
q_3	$-\frac{1}{3}e$	$\frac{1}{3}$	-1

construct Σ^- from the above quarks [q_2 q_2 q_3]

29. Identify the interaction responsible for the following decays

a) $\Delta^* \rightarrow p + \pi\ (10^{-23}s)$ c) $K^+ \rightarrow \mu^+ + \upsilon_\mu (\ (10^{-8}s)$

b) $\eta \rightarrow \gamma + \gamma(\ (10^{-18}s)$ d) $\Lambda^0 \rightarrow \pi + p\ (10^{-10}s)$ $\begin{bmatrix} \text{a) Strong} & \text{b) E.M} \\ \text{c) Weak} & \text{d) weak} \end{bmatrix}$

30. Name the conservation law that would be violated in each of the following

a) $\Lambda^0 \rightarrow p + K^-$ c) $\Xi^0 \rightarrow \Sigma^0 + \pi^0$

b) $\Omega^- \rightarrow \Xi^0 + K^-$ d) $\mu^- \rightarrow e^- + \gamma$

Given $m_\Lambda = 1116\ MeV/c^2$

$m_K = 494\ MeV/c^2$ $m_{\Xi^0} = 1315\ MeV/c^2$

$m_{\Sigma^0} = 1193\ MeV/c^2$ $m_{\pi^0} = 135\ MeV/c^2$

$\begin{bmatrix} \text{a) energy} & \text{b) energy} \\ \text{c) energy} & \text{d) } L_e \text{ and } L_\mu \text{ are not conserved} \end{bmatrix}$

31. Each of the following reactions violates one of the conservation laws. Identify it?

a) $\upsilon_e + p \rightarrow n + e^+$ (L_e not conserved)

b) $p + p \rightarrow p + n + K^+$ (S not conserved)

c) $\pi^- + n \rightarrow K^- + \Lambda^0$ (S not conserved)

32. A Σ^- baryon is produced in a certain reaction with a kinetic energy of 3642 MeV. If the particle decays after one meanlife time, what is the longest possible track this particle could leave in a detector. Proper life time of $\Sigma^- = 1.5 \times 10^{-10}$s and $m_{\Sigma^-} = 1197\ \text{MeV}/c^2$ [0.18m]

33. Find the Q-value of the following decay?

$$\pi^0 \rightarrow \gamma + \gamma$$

$m_\pi = 135\ \text{MeV}/c^2$ [135 MeV]

34. Find the kinetic energies of the two product particles in the given decay $K^0 \rightarrow \pi^+ + \pi^-$. Assume that decaying particle is at rest.

$E_{K^0} = 498\ \text{MeV}/c^2$ and $m_{\pi^+} = 148$ MeV $\left[K_{\pi^+} = K_{\pi^-} = 109\ \text{MeV}\right]$

35. A negatively charged sigma particle moving with a kinetic energy of 250 MeV decays into $\pi^- + n$. The π^- moves at 90° to the original direction of travel of the Σ^-. Find the kinetic energies of π^- and n and the direction of travel of n. $m_\Sigma = 1197\ \text{MeV}/c^2$ $m_\pi = 140\ \text{MeV}/c^2$ and $m_n = 940\ \text{MeV}/c^2$

36. Find the threshold kinetic energy of the following reaction:

$$p + n \rightarrow p + \Sigma^- + K^+$$

$m_p = 938\ \text{MeV}/c^2$, $m_n = 940\ \text{MeV}/c^2$,

$m_{\Sigma^-} = 1197\ \text{MeV}/c^2$ and $m_{K^+} = 494\text{MeV}/c^2$ [1800.4 MeV]

Section C

(*Answer questions in* **one** *or* **two** *pages*)

Long answer type questions (Essays)

1. Give an account of various conservation laws in particle reactions of elementary particles.
2. Derive and expression for relativistic threshold kinetic energy of particle reactions of elementary particles.
3. Give a detailed account of standard model

Hints to problems

22. a) $p + p \rightarrow n + p + \pi^+$

Check charge conservation - conserved check baryon number conservation – conserved. Check spin conservation – conserved.

b) $p + p \rightarrow p + \Lambda^0 + \Sigma^+$

B: 1 + 1 = 1 + 1 + 1 Baryon number not conserved

c) $e^- + e^+ \rightarrow \mu^+ + \pi^-$

Check charge conservation – not conserved

c) $p + p \rightarrow \pi^+ + K^o + \Lambda^o$

Charge is conserved
Baryon number is conserved

Spin is conserved
Strangeness is conserved

23. a) $K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$

Charge is conserved
Strangeness is not conserved

Spin is conserved

a) $K^+ \rightarrow \mu^+ + \upsilon$

Strangeness is not conserved

24. a) $\pi^- + p \rightarrow \Lambda^o + K^o$

Charge is conserved
Baryon number is conserved

Spin is conserved
Strangeness is also conserved

b) $K^- + p \rightarrow \Sigma^+ + \pi^-$

Charge is conserved
Baryon number is conserved

Spin is conserved
Strangeness is conserved

25. π^-, charge $= -1$, spin $= 0$, $S = 0$ and $B = 0$. To satisfy all these $\pi^- \equiv \bar{u}d$.

26. Charge of the particle uus $= \frac{2}{3} + \frac{2}{3} - \frac{1}{3} = 1$ The strangeness $S = -1$, Baryon number $= +1$ so the particle is Σ^+.

27. Check baryon number – not conserved check spin – not conserved.

28. For Σ^+, charge $= -e$, B.No $= 1$, strangeness $= -1$

Hence $q_2\ q_2\ q_3$.

29. a) Strong because of life time
b) Electromagnetic because of photons
c) Weak because of leptons
d) Weak because of the lifetime.

30. a) $\Lambda^o \rightarrow p + K^-$

$m_\Lambda c^2 < m_p c^2 + m_K c^2$

Law of conservation of energy is violated.

b) $\Omega^- \rightarrow \Xi^o + K^-$

$m_\Omega c^2 < m_\Xi c^2 + m_K c^2$

c) $\Xi^o \rightarrow \Sigma^o + \pi^0$

$m_\Xi c^2 < m_\Sigma c^2 + m_K c^2$

d) $\mu^- \rightarrow e^- + \gamma$

$L_e : 0 \rightarrow 1 + 0$ not conserved

$L_M : 1 \rightarrow 0 + 0$ not conserved

31. a) $\upsilon_e + p \rightarrow n + e^+$

$L_e : +1 + 0 \rightarrow 0 - 1$ Electron lepton number not conserved

b) $p + p \rightarrow p + n + K^+$

$S : 0 + 0 \rightarrow 0 + 0 + -1$ Strangeness number not conserved

c) $\pi^- + n \rightarrow K^- + \Lambda^0$

$S : 0 + 0 \rightarrow -1 + -1$ Strangeness number is not conserved

32. Total energy, $E = K + mc^2 = 3642 + 1197$

$E = 4839$ MeV

$$E = \frac{mc^2}{\sqrt{1 - v^2/c^2}} = 4839 \text{ MeV}$$

From this calculate $\frac{v}{c} = 0.9689$

$$\therefore \quad \tau = \frac{\tau_0}{\sqrt{1 - v^2/c^2}} = \frac{1.5 \times 10^{-10}}{\sqrt{1 - 0/9689}} = 6.07 \times 10^{-10} s$$

$\therefore$ Distance travelled $D = v\tau$

$$D = 0.9689\, c \times 6.07 \times 10^{-10}$$

$$D = 0.18 m$$

33. $Q = (m_i - m_f)c^2, \; m_f = 0$

$Q = m_\pi c^2 = 135$ MeV

34. $K^0 \rightarrow \pi^+ + \pi^-$

From momentum conservation

$$p_{K^0} = p_{\pi^+} + P_{\pi^-}$$

$$0 = p_{\pi^+} + P_{\pi^-}$$

Thus $|p_{\pi^+}| = |P_{\pi^-}|$

$\therefore \quad E_{\pi^+} = E_{\pi^-}$

From energy conservation

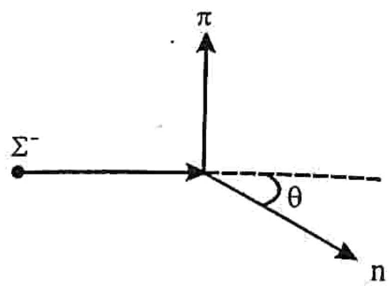
$$E_{K^0} = E_{\pi^+} + E_{\pi^-} = 2E_{\pi^+} \quad (\because \; E_{\pi^+} = E_{\pi^-})$$

$$\therefore \quad E_{\pi^+} = \frac{E_{K^0}}{2} = \frac{498}{2}\text{MeV} = 249 \text{ MeV}$$

$$K_{\pi^+} = E_{\pi^+} - m_\pi c^2 = 249 - 140 \text{ MeV}$$

$$= 109 \text{ MeV.}$$

35. $E_\Sigma = K_\Sigma + m_\Sigma c^2 = 250 + 1197 = 1447$ MeV



Using $E_\Sigma = \sqrt{(p_\Sigma c)^2 + (m_\Sigma c^2)^2}$

$$\therefore \quad p_\Sigma c = \sqrt{E_\Sigma^2 - (m_\Sigma c^2)^2} = \sqrt{1447^2 - 1197^2}$$

$$p_\Sigma c = 813 \text{ MeV}$$

The conservation of momentum gives x-direction:

$$p_\Sigma = p_n \cos\theta \qquad \text{.....(1)}$$

y-direction

$$O = p_n \sin\theta - p_\pi$$

$$p_\pi = p_n \sin\theta \qquad \text{..... (2)}$$

From eqn 1 and 2 we get

$$p_n^2 = p_\Sigma^2 + p_\pi^2$$

From conservation of energy

$$E_\Sigma = E_n + E_\pi$$

$$E_\Sigma = \sqrt{p_n^2c^2 + (m_n c^2)^2} + \sqrt{p_\pi^2 c^2 + (m_\pi c^2)^2}$$

$$\therefore \quad \sqrt{p_\pi^2 c^2 + (m_\pi c^2)^2} = E_\Sigma - \sqrt{p_n^2 c^2 + (m_n c^2)^2}$$

squaring

$$\therefore \quad p_\pi^2 c^2 + (m_\pi c^2)^2 = E_\Sigma^2 + p_n^2 c^2 + (m_n c^2)^2 - 2E_\Sigma \sqrt{p_n^2 c^2 + (m_n c^2)^2}$$

$$\therefore \quad 2E_\Sigma \sqrt{p_n^2 c^2 + (m_n c^2)^2} = E_\Sigma^2 + p_n^2 c^2 + (m_n c^2)^2 - p_\pi^2 c^2 - (m_\pi c^2)^2$$

$$\therefore \quad 2E_\Sigma E_n = E_\Sigma^2 + (p_\Sigma^2 + p_\pi^2)c^2 + (m_n c^2)^2 - p_\pi^2 c^2 - (m_\pi c^2)^2$$

$$\therefore \quad E_n = \frac{E_\Sigma^2 + p_\Sigma^2 c^2 + (m_n c^2)^2 - (m_\pi c^2)^2}{2E_\Sigma}$$

$$E_n = \frac{(1447)^2 + (813)^2 + 940^2 - 140^2}{2 \times 1447}$$

$$E_n = 1250\text{MeV}$$

$$K_n = E_n - M_n c^2 = 1250 - 940 = 310\text{MeV}$$

$$E_\pi = E_\Sigma - E_n = 1447 - 1250 = 197\text{MeV}$$

$$K_\pi = E_\pi - m_\pi c^2 = 197 - 140 = 57\text{MeV}$$

$$cp_n = \sqrt{E_n^2 - (m_n c^2)^2} = \sqrt{1250^2 - 940^2} = 824 \text{ MeV}$$

From eqn. 1 we get

$$\cos\theta = \frac{p_\Sigma}{p_n} = \frac{cp_\Sigma}{cp_n} = \frac{813}{824} = 0.9866$$

$$\theta = 9.37^\circ$$

36. $p + n \rightarrow p + \Sigma + K^-$

$$Q = (m_i - m_f)c^2$$

$$Q = (m_p + m_n - m_p - m_\Sigma - m_K)c^2$$

$$Q = (m_n - m_\Sigma - m_K)c^2$$

$$Q = 940 - 1197 - 494 \text{ MeV}$$

$$Q = -\ 751 \text{ MeV}$$

Threshold kinetic energy

$$K_{th} = \frac{-Q\,(m_p + m_n + m_p + m_\Sigma + m_K)}{2m_n}$$

$$K_{th} = -Q\frac{(2m_p + m_n + m_\Sigma + m_K)c^2}{2m_n c^2}$$

$$K_{th} = --751\frac{(2 \times 938 + 940 + 1197 + 494)}{2 \times 940}$$

$$K_{th} = 1800.4 \text{ MeV}$$